Material Efficiency & Resource Conservation

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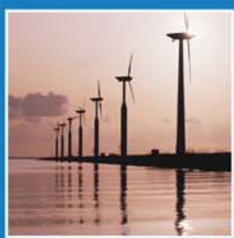
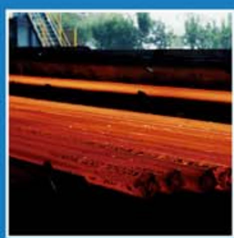
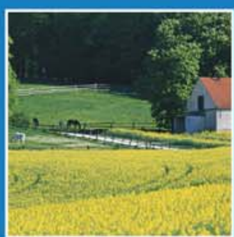
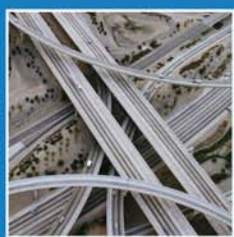
A service-oriented approach to defining eco-design requirements for lighting

Paper within the framework of the
„Material Efficiency and Resource Conservation“
(MaRess) Project – Task 14

ResourceEfficiency Paper 14.1

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Defining eco-design requirements for lighting

Contents

Tables

Figures

1 Introduction

In 2005 the European Union released the EuP Directive, focusing on environmental standards for energy using products (EU Parliament and Council of the EU 2005). This directive, also called Eco-Design Directive, is a framework directive, establishing a framework structure in which concrete requirements for individual products can be defined through so-called implementing measures. Some existing directives are already declared as being implementing measures of the Eco-Design Directive and additionally, new implementing measures are being developed. Product-specific preparatory studies on behalf of the European Commission have provided the basis for these.

Until the beginning of March 2008, the EU Commission has released three working documents on possible ecodesign requirements for lighting (general lighting, public street lighting, and office lighting). In the "**Working document on possible ecodesign requirements for general lighting equipment** ("Domestic lighting part 1, including incandescent bulbs")" (European Commission 2008), issued in March 2008 as the main discussion document for the Consultation Forum on "domestic lighting" on 28 March 2008, **three options for minimum energy efficiency requirements** are presented:

- Option 1: Phase out of all traditional incandescent bulbs (GLS), all halogen lamps and B+ level compact fluorescent lamps (CFLs)
- Option 2: Phase out of all GLS, all frosted halogen lamps, all high light output halogen lamps, average and poor (level C and D) clear halogen lamps, B+ level CFLs if they do not have excellent colour rendering
- Option 3: Phase out of all GLS, poor halogen lamps (level D)

These three options differ in the level of phase out of products and therefore in the efficiency of the remaining lamps on the market. Whereas option 1 would lead to a situation which is 4.6 times more efficient than average GLS, option 2 would lead to a 3.5 and option 3 to a 1.9 times more efficient situation than average GLS.

The presented options are partly based on the respective preparatory study, which the German Federal Environment Agency (UBA) already commented on (cf., e.g., Mordziol 2008; cf. also BAM/UBA for further general comments on how to set ecodesign requirements for lighting). So far, UBA introduced a **qualitative alternative proposal for a more systematic identification of minimum energy efficiency requirements** into the consultation process on EU-level, which

- is independent from lamp technology and instead concentrates on the service provided by a lamp (+ ballast) to the end-user,
- thereby takes additional services provided with a lamp besides a specific luminous flux into account (e.g. colour temperature, colour rendering index, reduced glare, prevention of environment from hazardous substances in case of lamp crash, focusability or concentration of light, etc.), and

- avoids inconsistencies in the definition of the minimum energy efficiency curve or maximum energy consumption curve.

In contrary to the EU proposal, a scheme for maximum electricity consumption of lamps (including ballasts) depending on the luminance Qv (in Mlmh) and on additional service-oriented product characteristics was provided. The main idea is to design a maximum requirement by the following formula:

Power demand P of lamp (+ ballast) [W] =
f (luminuous flux Φ [lm]; additional services provided),

or better, if typical usage patterns can be defined:

Power consumption E of lamp (+ ballast) [kWh] =
f (luminous energy Q_v [klmh]; additional services provided).

However, while several theoretical arguments can be put in favour of the UBA proposal, one important question remains:

Is the approach feasible, i.e. can the parameters and coefficients of such maximum functions be well-defined in a practicable and robust way?

- In order to support the examination of this central question, UBA has asked Wuppertal Institute to analyse, based on lamp-specific data from catalogues of lamp manufacturers, if this alternative proposal can be supported by statistical coherence, and if accordant quantitative efficiency requirements for lamps can be defined. The short expertise has been conducted in the framework of task 14 of the project "Materialeffizienz und Ressourcenschonung" (FKZ 3707 93 300) on behalf of the German Federal Ministry for Environment (BMU) and UBA.

2 Methodology

For this purpose, the following **hypotheses** have been examined in detail:

1. The definition of a maximum energy or power consumption requirement for lamps (+ ballast) independent from lamp technology is feasible (one function, one requirement for all lamp types).
2. If a lamp provides additional features/services besides luminous flux like a higher colour temperature, a higher colour rendering index, a reduced glare, a prevention of environment from hazardous substances in case of lamp crash or better focusability or concentration of light, etc., energy or power consumption will be significantly higher.
3. The coefficients for the different parameters of a maximum energy or power consumption requirement for lamps (+ ballasts) as proposed by UBA can be determined based on statistical analysis of catalogue data from manufacturers.

In order to carry out a quantitative analysis of these hypotheses an already initiated data base on lamp-specific data by UBA was further extended. This data has been statistically analysed according to statistical significance and size of individual factors (service-oriented product characteristics). The following factors have been considered as factors influencing energy or power consumption of a lamp (+ ballast):

- Luminous flux,
- Colour temperature,
- Colour rendering index,
- Bulb design: frosted glass,
- Bulb design: coloured glass,
- Splinter shield, protection glass or similar,
- Focusability of light due to compactness of the lamp and concentration of light by the lamp, and
- Dimmability.

Tab. 1 shows a more detailed definition of each variable.

Tab. 1: Definition of data as incorporated in the statistical analysis

Variable	Full name	Unit	Comment	Type of variable
Power	Power demand	W	Ideally, this would be power consumption in kWh. In order to simplify, power demand was chosen as variable.	Regressant, dependent variable
Flux	Luminuous flux	lm	This variable is run in all regressions; it will explain the biggest part of variance of power.	Main regressor
Ra	Colour rendering index	%	If only the according DIN-level is given (e.g. 1b), approximation through mean of respective level.	Additional regressors
Temp	Colour temperature	K	Colinearity with Ra? If applicable, dummy variable for daylight-similar light later on?	
BulbM	Bulb design: Frosted glass	Dummy: 0, 1	n.a. or clear = 0; frosted = 1	
BulbC	Bulb design: Coloured glass	Dummy: 0, 1	n.a. or clear oder white = 0; read or other colour = 1	
Prevent	Splinter shield, protection glass, or similar	Dummy: 0, 1	n.a. or no prevention = 0; with prevention = 1	
Focus	Focusability of light due to compactness of the lamp and concentration of light by the lamp	1 / [sr * m2]	Approximation through quotient out of medium luminance (in cd/cm2) and luminous flux (in lm). If applicable, later on there might be a more specific calculation through two variables: Focusability as function of the dimension of the light-emitting surface; Concentration as function of the reflection angle.	
Dimm	Dimmable	Dummy: 0, 1	n.a. or not dimmable = 0; dimmable = 1	
Lamp	Lamp type	1 = Incandescent 2 = Halogen 3 = CFL integrated 4 = CFL non integrated 5 = Fluorescent 6 = Induction 7 = Compact High Intensity Discharge 8 = High Intensity Discharge 9 = Traffic 10 = LED 11 = Special	For determination of lamp types; for carrying out statistical analyses not only for whole data base but also for certain lamp types; if applicable, runs will be taken without 9-11	Neither regressant nor regressor; filter variable

For these factors and their relation to power demand of a lamp (+ ballast), descriptive statistics as well as several runs of linear and non-linear regressions have been carried out with the help of SPSS software.

3 Data

The data input for the statistical analysis was taken from Philips Catalogue "Lamps and Gear 2006-2007" (Philips 2006). The decision for Philips data is based on its broad supply of lamps and particularly on the completeness of available data. Philips offers a product catalogue online and in print; however information on all covered product characteristics are not available for each lamp type.

Tab. 2: Overview of Philips Product Sheets considered in the statistical analysis

Selected Philips Product Sheets – Lamps & Gear 2006-2007	
Incandescent	Standard (T/A/E-shape)
	Candle (B-shape)
	Lustre (P-shape)
Halogen	Low Voltage Halogen with Reflector
	Low Voltage Halogen without Reflector
	Medium Voltage Halogen with Reflector
	Medium Voltage Halogen without Reflector
Compact Fluorescent Integrated (CFL)	Energy Saver Stick shape
	Energy Saver Bulb shape
Compact Fluorescent Non Integrated	PL-S
	PL-C
Fluorescent Lamps	TL5
Induction Lamps	Master QL-System
Compact High Intensity Discharge	MASTERColour CDM
High Intensity Discharge Lamps	MH/HPI Metal Halide
	Outdoor Ceramic White Light
	SON High Pressure Sodium
	SOX Low Pressure Sodium
Traffic Lamps	Traffic Halogen Single Ended
	Traffic Halogen Fiber Optics MR16
LED Lighting Systems	LED String System
Special Lighting	Broadway HID
	Broadway Halogen
	Focusline HID
	Focusline Halogen
	Colour & Blacklight Blue
	CLEO Suntanning/Bodycare
Lamp Drivers / Ballasts	HID electromagnetic

Caused by the short time available for writing this paper and due to lack of data availabilities, it was neither possible to include all existing Philips data nor to consider data from other lamp manufacturers like Osram, GE, Megaman, Narva, Radium, etc. However, it was taken care of that a selection of all lamp types was included. Tab. 2 shows which lamp types are considered in the statistical analysis.

Though not all data could be covered, in total 508 cases were considered in the statistical analysis, for which data on both power consumption and luminious flux was available in the Philips catalogue. The following tables show the frequency of lamp types covered and some descriptive statistics with regard to the data analysed.

Tab. 3: Frequencies with regard to lamp types covered by the analysis

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Incandescent	134	26,4	26,4	26,4
	Halogen	49	9,6	9,6	36,0
	CFL	51	10,0	10,0	46,1
	CFL non integrated	36	7,1	7,1	53,1
	Fluorescent	48	9,4	9,4	62,6
	Induction	8	1,6	1,6	64,2
	Compact High Intensity	11	2,2	2,2	66,3
	High Intensity Discharge	91	17,9	17,9	84,3
	Traffic	27	5,3	5,3	89,6
	LED	8	1,6	1,6	91,1
	Special	45	8,9	8,9	100,0
	Total	508	100,0	100,0	

Source: own calculation

Tab. 4: Descriptive statistics

		Power	Flux	Ra	Temp	BulbM	BulbC	Prevent	Focus	Dimm
N	Valid	508	508	508	508	508	508	508	508	508
	Missing	0	0	0	0	0	0	0	0	0
Mean		190,81175	10679,13	65,49	1811,32	,11	,50	,00	,07	,63
Median		52,50000	1160,00	82,00	2000,00	,00	,00	,00	,00	1,00
Std. Deviation		392,672497	28610,077	40,023	1834,158	,313	,500	,000	,812	,482
Variance		154191,690	818536526,59	1601,879	3364134,943	,098	,250	,000	,660	,233
Minimum		,095	2	0	0	0	0	0	0	0
Maximum		2500,000	220000	100	6800	1	1	0	11	1

Source: own calculation

4 Preliminary results

The analysis shows, of course, a strong statistical correlation between POWER and FLUX (0.805). The respective correlation tables as well as the scatter plots of these and other variables can be seen below.

Tab. 5: Correlation analysis

			Power	Flux
Spearman's rho	Power	Correlation Coefficient	1,000	,805(**)
		Sig. (2-tailed)	.	,000
		N	508	508
	Flux	Correlation Coefficient	,805(**)	1,000
		Sig. (2-tailed)	,000	.
		N	508	508

** Correlation is significant at the 0.01 level (2-tailed).

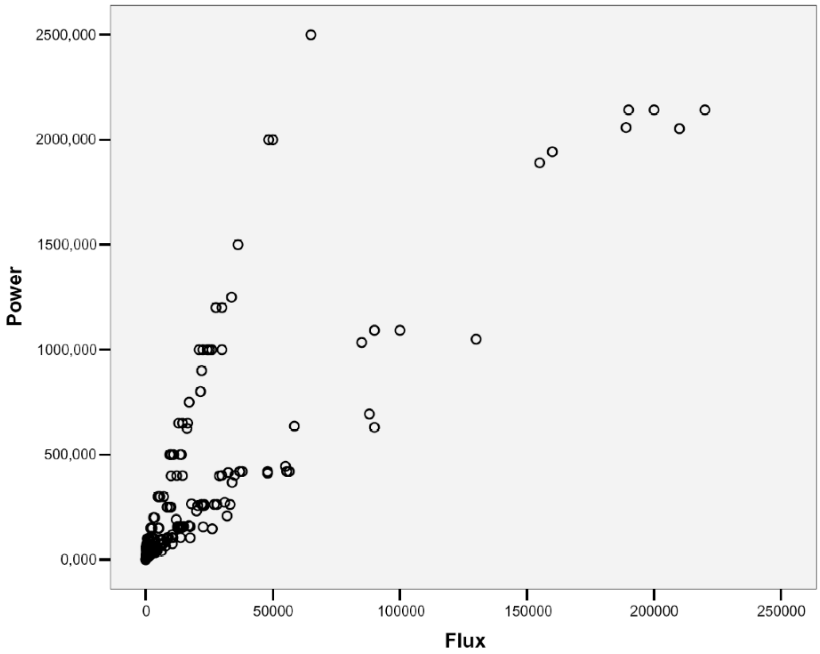
			Flux	Ra	Temp	BulbM	BulbC	Prevent	Focus	Dimm
Spearman's rho	Flux	Correlation Coefficient	1,000	-,449(**)	,305(**)	-,288(**)	,049	.	,404(**)	-,182(**)
		Sig. (2-tailed)	.	,000	,000	,000	,267	.	,000	,000
		N	508	508	508	508	508	508	508	508
	Ra	Correlation Coefficient	-,449(**)	1,000	,016	,411(**)	-,314(**)	.	-,114(**)	,465(**)
		Sig. (2-tailed)	,000	.	,722	,000	,000	.	,010	,000
		N	508	508	508	508	508	508	508	508
	Temp	Correlation Coefficient	,305(**)	,016	1,000	-,228(**)	,330(**)	.	,319(**)	-,253(**)
		Sig. (2-tailed)	,000	,722	.	,000	,000	.	,000	,000
		N	508	508	508	508	508	508	508	508
	BulbM	Correlation Coefficient	-,288(**)	,411(**)	-,228(**)	1,000	-,349(**)	.	-,169(**)	,268(**)
		Sig. (2-tailed)	,000	,000	,000	.	,000	.	,000	,000
		N	508	508	508	508	508	508	508	508
	BulbC	Correlation Coefficient	,049	-,314(**)	,330(**)	-,349(**)	1,000	.	,232(**)	-,439(**)
		Sig. (2-tailed)	,267	,000	,000	,000	.	.	,000	,000
		N	508	508	508	508	508	508	508	508
	Prevent	Correlation Coefficient	.	.	.	.	.	.	.	.
		Sig. (2-tailed)	.	.	.	.	.	.	.	.
		N	508	508	508	508	508	508	508	508
	Focus	Correlation Coefficient	,404(**)	-,114(**)	,319(**)	-,169(**)	,232(**)	.	1,000	,107(*)
		Sig. (2-tailed)	,000	,010	,000	,000	,000	.	.	,015
		N	508	508	508	508	508	508	508	508
	Dimm	Correlation Coefficient	-,182(**)	,465(**)	-,253(**)	,268(**)	-,439(**)	.	,107(*)	1,000
		Sig. (2-tailed)	,000	,000	,000	,000	,000	.	,015	.
		N	508	508	508	508	508	508	508	508

** Correlation is significant at the 0.01 level (2-tailed).
* Correlation is significant at the 0.05 level (2-tailed).

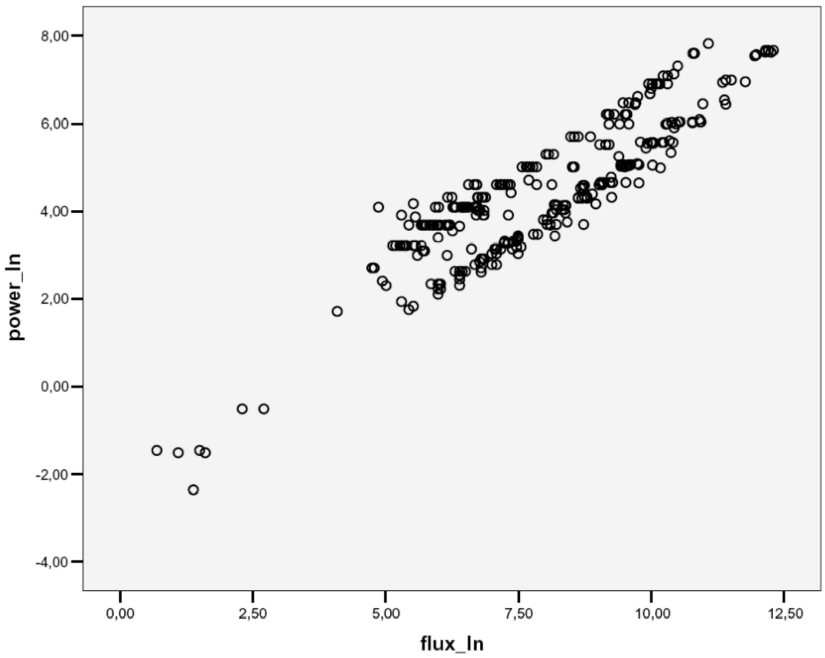
Source: own calculation

Fig. 1: Scatterplots

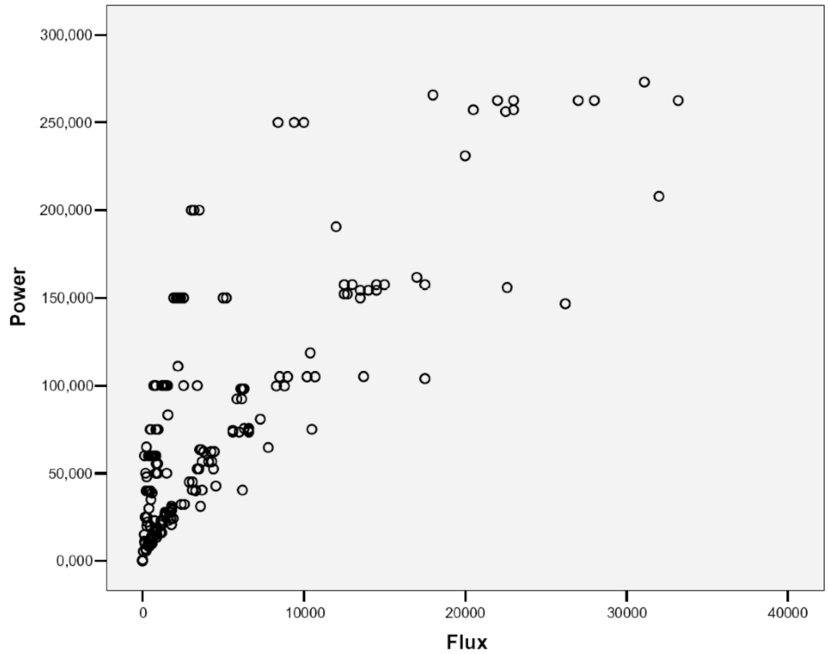
a) POWER vs. FLUX, all cases: The scatterplot suggests to split the data up into an efficient and a less efficient path



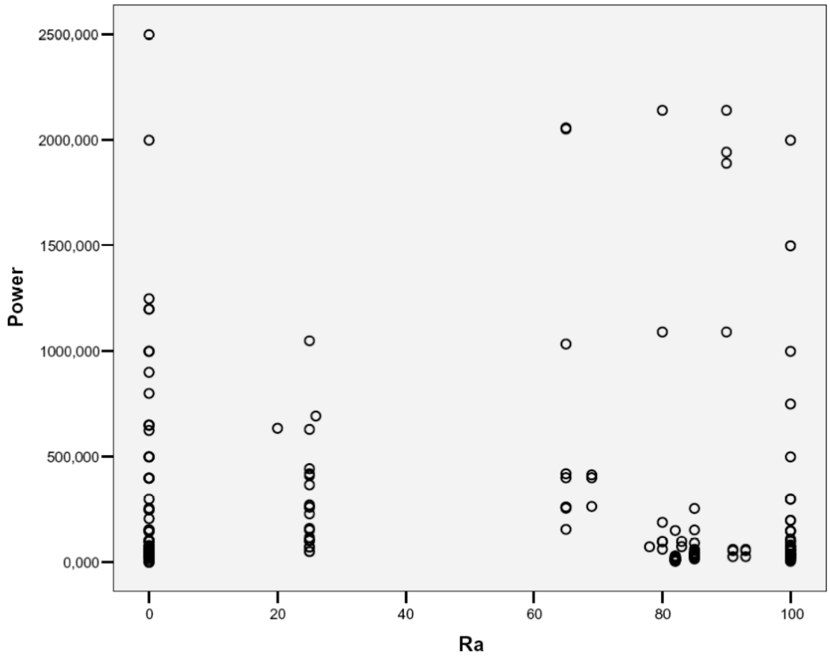
b) ln(POWER) vs. ln(FLUX), all cases



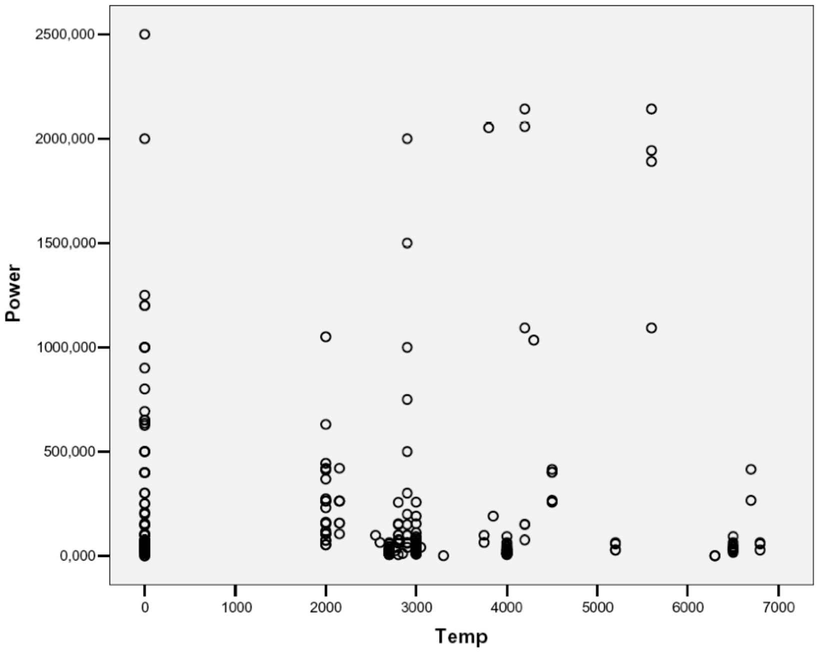
c) POWER vs. FLUX, with all cases for which POWER < 301 W: The scatterplot makes clear that the situation is more complex than suggested in a) and b)



d) POWER vs. RA, all cases



e) POWER vs. TEMP, all cases



Source: own calculation

The differences between means and medians in the descriptive statistic table already indicate that the distribution of lamps does not follow a normal distribution. However, although this central assumption is not fulfilled, different kind of regression analyses and tests were carried out on the assumption of normal distribution:

- linear and non-linear regressions including curve fits,
- regressions with all variables, regressions with selected regressors, and stepwise procedures (forward and backward),
- regressions with and without estimate of constants.

Since the White test confirmed that heteroskedasticity can be observed (rejection of the hypothesis of homoskedasticity), regressions were also carried out with correction for heteroskedasticity by weighting POWER by “1/unstandardised residuals”.

All these regressions were run

- for all 508 cases,
- for all cases but excluding traffic lamps and special lamps (436 cases),

for those (more efficient) lamps that fulfil the following requirement: POWER < 0.024 Flux (229 cases). This requirement was developed by roughly drawing a line between the two efficiency paths shown in the first of the above scatterplots.

Material Efficiency & Resource Conservation

Tab. 6: Results for 'all cases' (with t-values in italic below the co-efficients)

	dependent variable	independent variable										Model indicators				Method	Comment
		Constant	Flux	Ra	Temp	BulbC	BulbM	Focus	Dimm	ln (Flux)	Root (Flux)	Adjusted R^2	Std. Error of the Estimate	df	F		
all cases	Power	152.946	0.011	-1.476	-0.007	-67.939	-65.194	-13.902	106.179			0.751	196.058713	507	219.107	Enter	
		5.769	*32.996*	*-5.745*	*-1.195*	*-3.005*	*-2.042*	*-1.273*	*4.831*								
	Power	no	0.012	-0.954	-0.005	11.109	-43.352	-16.411	183.577			0.785	202.277375	508	265.952	Enter	
			37.26	*-3.845*	*-0.856*	*0.599*	*-1.326*	*-1.458*	*10.221*								
	Power	no	0.005	-0.509	-0.017	-53.08			80.962		2.603	0.822	184.133085	508	391.539	Stepwise (Model 6)	
			6.977	*-2.386*	*-3.001*	*-3.011*			*4.359*		*10.362*						
	ln (Power)	no								0.558		0.969	0.762	508	16075.938	ln-function (curve fit)	
										126.791							
	Power	no	0.012	-0.954	-0.005	11.109	-43.352	-16.411	183.577			0.788	202.277375	508	265.952	Enter	cases weighted by 1/unstandardized residuals
			37.26	*-3.845*	*-0.856*	*0.599*	*-1.326*	*-1.458*	*10.221*								
	Power	no	0.01	-0.147	-0.006	-0.475	-25.118	-7.069	76.015		0.403	0.924	9.35393	508	767.592	Enter	cases weighted by 1/unstandardized residuals
			32.92	*-1.526*	*-4.021*	*-0.094*	*-4.066*	*-2.282*	*8.215*		*4.854*						

Source: own calculation

Tab. 7: Results for all lamps except the lamp types “Traffic” and “Special”’ (with t-values in italic below the co-efficients)

	dependent variable	independent variable										Model indicators				Method	Comment
		Constant	**Flux**	**Ra**	**Temp**	**BulbC**	**BulbM**	**Focus**	**Dimm**	**ln (Flux)**	**Root (Flux)**	**Adjusted R²**	**Std. Error of the Estimate**	**df**	**F**		
without lamp type "Traffic" and "Special"	Power	7.873	0.01	0.665	0.007	-62.795	-35.567	4.183	0.157								
		0.419	*51.093*	*3.532*	*2.046*	*-4.583*	*-1.948*	*0.671*	*0.012*			0.893	110.877941	435	518.583	Enter	
	Power	no	0.01	0.709	0.007	-59.691	-34.472	4.279	2.385			0.909	110.771395	436	625.791	Enter	
			54.761	*4.549*	*2.128*	*-5.182*	*-1.91*	*0.688*	*0.19*								
	Power	no	0.009	0.685		-64.561	-39.728				0.689	0.913	108.705387	436	912.618	Stepwise (Model 5)	
			19.52	*6.788*		*-6.196*	*-2.287*				*4.44*						
	ln (Power)	no								0.538		0.97	0.719	436	13957.142	ln-function (curve fit)	
										118.14							
	Power	no	0.01	0.524	0.004	-40.088	-18.691	3.225	2.983			0.982	6.329673	436	3486.265	Enter	weighted by 1/unstandardized residuals
			135.057	*12.562*	*4.045*	*-11.632*	*-4.646*	*3.344*	*0.978*								
	Power	no	0.01	0.536	0.003	-42.116	-19.13	3.248	0.196		0.116	0.983	6.299581	436	3080.33	Enter	weighted by 1/unstandardized residuals
			63.193	*12.809*	*2.902*	*-11.88*	*-4.772*	*3.383*	*0.06*		*2.26*						

Source: own calculation

Tab. 8: Results for cases selected by condition Power < 0.024 Flux (with t-values in italic below the co-efficients)

	dependent variable	independent variable										Model indicators				Method	Comment
		Constant	Flux	Ra	Temp	BulbC	Bulb M	Focus	Dimm	ln(Flux)	Root (Flux)	Adjusted R^2	Std. Error of the Estimate	df	F		
cases selected by condition Power < 0,024 Flux	Power	no	0.01	0.626	0.012	-55.686		7.911	-40.118			0.986	55.064297	229	2690.429	Enter	
			99.17	*3.958*	*4.123*	*-6.079*		*2.511*	*-5.196*								
	Power	-34.139	0.01	0.648	0.015	-36.799		8.3	-36.57			0.983	54.160952	228	2250.708		
		-2.916	*93.26*	*4.156*	*5.009*	*-3.316*		*2.677*	*-4.755*								
	Power	no	0.01	0.626	0.012	-55.686		7.911	-40.118		…	0.986	55.064297	229	2690.429	Stepwise (Model 6	Root (Flux) contained but without significant result
			99.17	*3.958*	*4.123*	*-6.079*		*2.511*	*-5.196*								
	Power	no								0.506		0.978	0.646	229	10392.844	ln-function (curve fit)	
										#							
	Power	no	0.01	0.516	0.009	-46.025		6.256	-29.774			0.994	5.669841	229	5892.684	Enter	weighted by 1/unstandardized residuals
			163.875	*7.547*	*8.28*	*-10.568*		*5.157*	*-11.435*								
	Power	no	0.01	0.506	0.009	-45.273		6.267	-29.582		-0.023	0.994	5.678588	229	5035.368	Enter	weighted by 1/unstandardized residuals; Root (Flux) contained but without significant result
				7.127	*8.033*	*-9.92*		*5.157*	*-11.247*		*-0.56*						

Source: own calculation

5 Conclusions

With regard to the three hypotheses presented in the beginning, the following conclusions can be deducted from the analysis:

1. The analysis confirms that the definition of a maximum energy or power consumption requirement for lamps (+ ballast) independent from lamp technology is feasible (one function, one requirement for all lamp types). Some of the regressions show a very high adjusted R-square up to 0.994, i.e. that the regressors included into the regression explain nearly all of the variances of the regressand. This is particularly true for the regressions run on the efficient lamps only and on all cases except traffic and special lamps.
2. The statistical analysis shows mixed results with regard to the influence of the different additional lamp features / service-oriented product characteristics besides the luminous flux on POWER. The degree of significance differs from regression to regression as well as the size and even the algebraic sign of coefficients. Furthermore, the size and sign of coefficients (statistical relationship) can often not be explained by available knowledge on lamp technology (causal relationships).
3. Therefore, it does not seem to be possible to determine a quantitative energy efficiency requirement for lamps that includes supplements for additional lamp features / service-oriented product characteristics based on a pure statistical analysis of (this set of) catalogue data from manufacturers. Further technical reflections on causal relationships will be needed.

The principle idea of a systematic identification of minimum energy efficiency requirements independent from lamp technology and instead concentrating on the service provided by a lamp (+ ballast) to the end-user and developing a minimum energy efficiency requirement depending on different criteria specifying the quality of this service, has been strongly supported by Mr Stefan Gasser, S.A.F.E., who commented on an earlier version of this paper. He recommended to develop such an energy performance standard in close co-operation with industry and based on a larger set of data.

From his experience, important variables to be considered in the formula should be: the colour rendering index (RA), the focusability (FOCUS), and – not considered in the statistical analysis presented here – the lamp warm-up time, the lamp lifetime, the lumen maintenance, the number of switching cycles, and the temperature at which the lamps are usually used (since fluorescent lamps have difficulties at temperatures lower than -10° C and higher then +50°C). With regard to the variable PREVENT, he recommended to check if this should be really considered for the lamps or if the luminaires could provide the protection needed. In addition, with regard to the variable BulbC, it should be considered that LED could provide energy-efficient coloured light. According to his recommendations, TEMP and DIMM should not be considered as variables to be included into the formula.

6 References

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